DESIGN AND OPERATIONAL ASPECTS OF DIESEL GENERATORS' POWER AND NUMBER FOR SEAGOING SHIPS

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Abstract

New chapter 4, added to Annex VI of MARPOL convention, put into effect regulations on the ships 'energy efficiency. It makes mandatory since 1st January 2013 the so called Energy Efficiency Design Index (EEDI) for new ships and the Ship Energy Efficiency Management Plan (SEEMP) for new and existing vessels of 400 gt and above. There is a huge space to save the energy, improve the ships' efficiency and reduce the GHG emissions for the sea going ships such as container carriers are.

The aspects presented in the paper are based on the contemporary container vessels with the state of the art technology implemented to their design and operational stage. The estimation of the electric power and number of diesel generators with use of the statistical tools is the main aim of the paper. The container vessels fitted only with the diesel generators without any other type of electric generator unit are taken into account in the calculation process. The electric power equation has been determined, applying the multiple regression model with an absolute term, based on the ship's parameters for the entire range of the container vessels' load capacity TEU. It shown, the reefer containers RC and the main propulsion rating SMCR are the most important parameters statistically significant. It is calculated as well how the total ship's electric power is very strictly dependent on the number of diesel generators installed on board.

The reefer containers' number and its assumed power considering the cargo type and the simultaneity coefficient are also presented in the article, as this impact the electric power demand. The different types of Power Management Systems for diesel generators load are discussed at the last stage of the paper.

Keywords: *seagoing ships, diesel generators, electric power, PMS, reefer containers*

1. Introduction

Despite global recession, that has an effect on marine transport, and the fuel prices remaining persistently high at approximately 600 US dollars per metric tonne, there are many very large and ultra large carriers on order to be launched very soon and just delivered. Containers up to 18 000 TEU capacity are those ships that are favourable in these size are.

The utmost importance is the electric power production, demand and distribution in such a way to make the seagoing ships energy efficient with reduction of fuel and lubricating oil consumption. The achievement can be made at the design stage based on the energy efficiency design index EEDI and at operational stage monitored by the energy efficiency operational indicator EEOI within the ship energy efficiency management plan SEEMP. Both, index and plan are mandatory by Chapter 4 to Annex VI of the MARPOL 73/78 convention.

One of the energy efficient aspects beside the main propulsion engine is the right design of the number and power of the diesel generators.

High number of reefer containers on board comes up to 1500 units. This is why the container vessels, during the sea voyage between ports, require additional electric power to be supplied comparing to the other ship's types. Part of these containers are loaded in designated cargo holds what requires additional electric power to supply the fans as well.

2. Reefer container electric power determination

The container vessels are the ships with relatively high electric power demand that comes from the reefer containers' power supply among other things.

It must be bear in mind, the capacity of container vessels is designed in TEU number and the reefer containers transferred by container carriers are generally FEU types. It can be said the FEU is twice bigger in capacity than TEU.

Depends on the type of shipped cargo either chilled or deep-frozen in the container, the electric power demand of the FEU reefer container is different. The right value of the reefer container electric power is presented in Fig. 1.

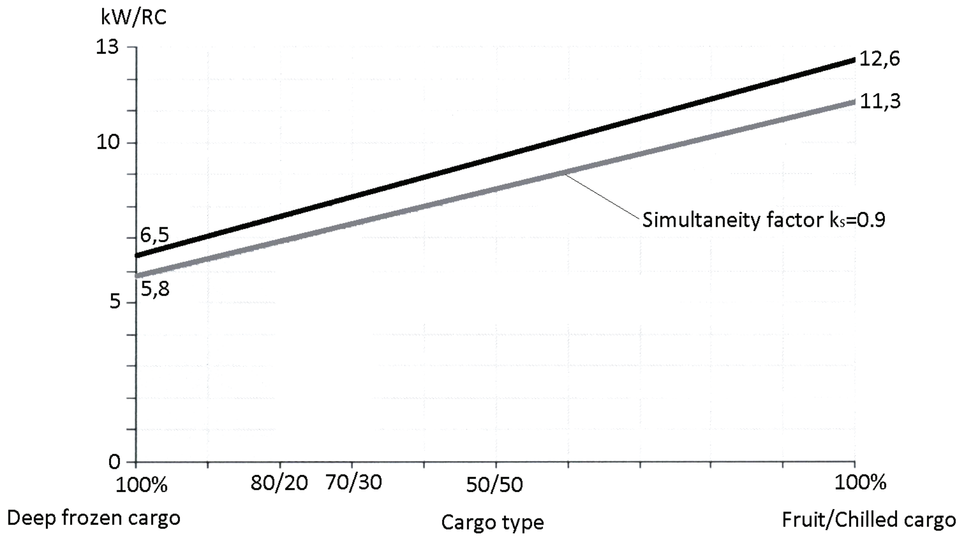

Fig.1. Electric power demand for reefer container 0

Based on Fig. 1, the reefer container electric power in kW, considering cargo type k_c shows that if the temperature is lower the assumed power per one reefer container RC can be lowered in the electric balance calculations. In case the reefer container RC is loaded with the fruits only, the power of 11.3 kW can be assumed. On the other hand if the reefer container is filled with frozen cargo i.e. fish, the power of 5.8 kW, that is twice less, can be assumed [4]. This power is predicted, considering the number of reefer containers working simultaneously. The so-called simultaneity coefficient k_s in the relationship (1) can be assumed at the level of 0.9 and finally is changed into formula (2). The power calculated with formula either (1) or (2) in the given range that is 70% of deep frozen cargo and 30% chilled cargo up to 80% of deep frozen cargo and 20% chilled cargo type respectively, gives the 6.9 kW designed load:

$$12.6\, k_c\, k_s = 6.9\,\text{kW}\,. \tag{1}$$

With the deep frozen cargo, the coefficient k_s can be even lower:

$$11.3\, k_c = 6.9\,\text{kW}\,, \tag{2}$$

where $k_c = 7.72 / 12.6 = 0.61$.

Based on the author's data base [1] the number of reefer containers referred to the designed total number of the ship's containers has been presented in Tab. 1.

The values presented in table 1 show that 90% of container ships are designed in such a way that the number of reefer containers RC are 5% up to 20% of the ship's containers' total number. Approximately 45% of considered vessels are in range of 5% up to 10%. The mean value of the reefer containers RC related to the ship containers' total number according to the data presented in Tab. 1 is at the level of 12%.

Tab.1. The percentage value of reefer containers in the total number of ship's containers

Percentage quota of reefer containers in the total number of ship's containers	Container ships percentage value in data base
≤ 5.0	4.1
5.1 up to 10.0	43.3
10.1 up to 15.0	24.6
15.1 up to 20.0	19.9
20.1 up to 25.0	7.0
25.1 up to 30.0	0.6
≥ 30.1	0.6

3. Electric power estimation

The correct selection of the electric system and its power, taking into account the operational aspects gives the opportunity to use the existing seagoing ships data. The relations between the ship's basic construction parameters and the total, nominal electric power of the diesel generators were study to determine the vessel's electric power demand.

Based on the regression model, used in the design methods by Scott, Holtrop, Mennen, the relationship was determined for the electric power installed on the container ships. General form of multiple regression equation with an absolute term is presented in the formula (3). The absolute term represents parameters, that can make an effect on the final result of regression equation, as were not taken into account in the statistical process.

$$P_{el} = a + b_1 X_1 + b_2 X_2 + \ldots + b_z X_z \,, \tag{3}$$

where:
a – absolute term,
$b_1, b_2, \ldots b_z$ – regression coefficient related to the ship's technical parameters,
$X_1, X_2, \ldots X_z$ – ship's technical parameters or its product.

Taking into consideration different units of the independent variables p, the standardized regression coefficient BETA for every independent variable is also presented besides the significant level in the statistical calculations.

The independent variables were considered as listed:
TEU – number of Twenty feet Equivalent Unit [–],
RC – number of reefer containers [–],
v – ship's speed [kn],
SMCR – specified maximum continuous rating [kW],
LBT – main dimensions product [m^3],
Z – complimentary [–],
P_{ss} – bow thruster power [kW].

For such variables, the basic calculations were made to evaluate how the dependent variable is affected by the independent variables with significant level at the limit of $p \leq 0.05$. Bellow the value the results were considered as statistically important.

Making analysis of independent variables on electric power it gave the result that only two parameters were statistically important, that is number of reefer containers and the main engine power described as SMCR. For both of these parameters and the absolute term the significant level p has got acceptably low statistical values.

To increase the precision of the findings before the final equation was derived, the residuum and eliminated residuum analysis were carried out.

For the multiple regression method, the results were achieved for standardized regression coefficient BETA, multiple regression coefficient b and significant level p. The values are presented in Tab. 2.

Tab. 2. Statistical results of multiple regression analysis for the ships' electric power

Parameter	Symbol	BETA	b	p
Absolute term	–	–	515.23	0.02
Reefer containers	RC	0.49	6.87	0.00
Main engine power	SMCR	0.54	0.08	0.00

The BETA coefficient allows to compare relative dependence, which every independent variable influence the dependence variable, that is installed ship's electric power. Other words, BETA coefficient standardized the variables to check out their influence on the dependent variable irrespectively of each independent variable unit.

The BETA parameter with a value of 0.49 presented in Tab. 2, means that the number of reefer containers has comparable effect to the electric power value as the main engine power SMCR has.

Very good values of the significant level emphasize the statistic importance of obtained multiple regression equation. Other factors of statistic analysis have got the constant values respectively: the correlation coefficient $R = 0.95$, determination coefficient $R^2 = 0.90$ and the estimation deviation 970.63.

Finally the multiple regression equation with the absolute term based on the full range of the container carriers, where the total electric power is created only by the diesel generators, is presented in the formula (4).

$$\mathrm{P_{el}} = 6.87\,\mathrm{RC} + 0.08\,\mathrm{SMCR} + 515.23\,. \tag{4}$$

There are only two independent values in the equation (4) that is number of reefer containers RU and the main engine power SMCR. The power SMCR represents the vessel's designed number of twenty feet containers TEU and the designed ship's speed v.

4. Selection of diesel generators' number

Once the ship's total electric power is already estimated, the selection of correct number of diesel generators is the next step in the calculation process. The safety and operational aspects, classification society's requirements and the acquisition expenses for the chosen electric configuration must be considered.

Each ship must be fitted with sufficient electric power to supply the essential units, taking mainly into consideration the ship's en route and its manoeuvrings. Such an electric supply source must consist of at least two independent generators. The power and number of diesel generators as a basic electric source ought to be configured in such a way, that in case of one diesel generator fails the other must generate sufficient power to supply essential units to continue the ship's voyage with a cargo in a safe manner.

The diesel generators power distribution is different, based on the electric demand and the number of installed diesel generators for a given ship. Generally the ship's electric power demand considering the number and power of diesel generators can be calculated with a formula (3).

$$P_{Del} = \frac{P_{el}}{d}(d-1)\ [\mathrm{kW}]\,, \tag{5}$$

where:
P_{Del} – ship's electric power demand,
P_{el} – totally installed ship's electric power,
d – number of diesel generators.

The equation (5), determining the electric power, has been statistically obtained based on the number and power of diesel generators installed in the engine room. Utilizing the relationship (5) a selection of diesel generators' number with the same power, is presented in Tab. 3 assuming the

Tab. 3. Number and electric power of diesel generators

Number of diesel generators [pcs]	Ship's electric power demand [kW]	Diesel generator electric power [kW]	Total ship's electric power [kW]
2	1000	1000	2000
3	1000	500	1500
4	1000	333	1332
5	1000	250	1250
6	1000	200	1200

ship's electric power demand is 1 000 kW. According to the classification societies, if two diesel generators are installed, each one separately must provide the safe operation of the ship. Thus every diesel generator must be able to generate 1 000 kW. The total ship's electric power is the highest in such a case, that is 2 000 kW. The least total ship's electric power 1 200 kW is installed to the ship fitted with 6 diesel generators, each one producing 200 kW. The ship's electric power demand P_{Del} of 1 000 kW is generated by other 5 ones in case of failure one of them.

The most favourable design, based on the considering type of container vessels, is the electrical system on board served by four diesel generators 0. Those generators are installed mainly in two different configurations with either two sets of the same, higher power and other pair with the same, smaller power or all four-diesel generators with the same nominal electric power.

Many aspects must be considered to make a right choice of the number and power of diesel generators. Apart from the durability and tribology wear, the ship's safety is crucial determinant as well as power management system, the classification societies' requirements etc. It is important to keep the diesel engines as high as possible load as the generator efficiency and specific fuel oil consumption is better. For the sake of the ships' ancillary systems functionality, considering the small power units switch on necessity, the electric auto control system is designed with approximately 15% of indispensable reserve of diesel generator nominal electric power. Such a value is in range of the most often load rise demand that is between 3-15%.

5. Power Management Systems

Every electric distribution system of seagoing ship is supported by the system called full automation arrangement or continuous power supply. Its aim is the safety considerations and economic management of the electric power availability.

In case the electric power demand comes up to the set up value, the next diesel generator is activated, synchronized and power shared with the running ones. If the electric power demand falls down to the limited value, one of the diesel generators is switched off according to the stopping procedure. The safety and the economic operation is very often the inverse state for the ship, especially during manoeuvrings. To find the safety and economic management of the available electric power compromise, different ideas of automation systems controlling the diesel generators are used. The diesel generators load can be controlled depends on the engaged system either symmetrically or asymmetrically. There is such a possibility of the electric power management system's settings that the generators are evenly electric power distributed. The ”Unbalancing Load” option in the asymmetrical load allows sharing the power in such a way that the master generator is loaded with 85% of its nominal power and the slave diesel generator takes over the remaining load. It is possible, adjusting the settings of the power management system and using the ”Load stop blocked” option, neglecting actual electric power demand, the diesel generators are working in the parallel mode even with a very small load.

Apart from the above, the configuration with either absolute power margin or with constant power margin in the power management systems are available. The purpose of such design is presented in Tab. 4 with visualization shown in Fig. 2.

Tab. 4. The load of diesel generators for different PMS

	1. Absolute power margin			2. Constant power margin		
Number of diesel generator	1	2	3	1	2	3
Start term	85%	85%	—			
Min load once synchronized %	0	42.5	56.7	0	42.5	61.7
Power margin for start	15	30	—	15	15	—
Stop	1	2	3	1	2	3
Load %	—	35.0	51.7	—	35	56.7

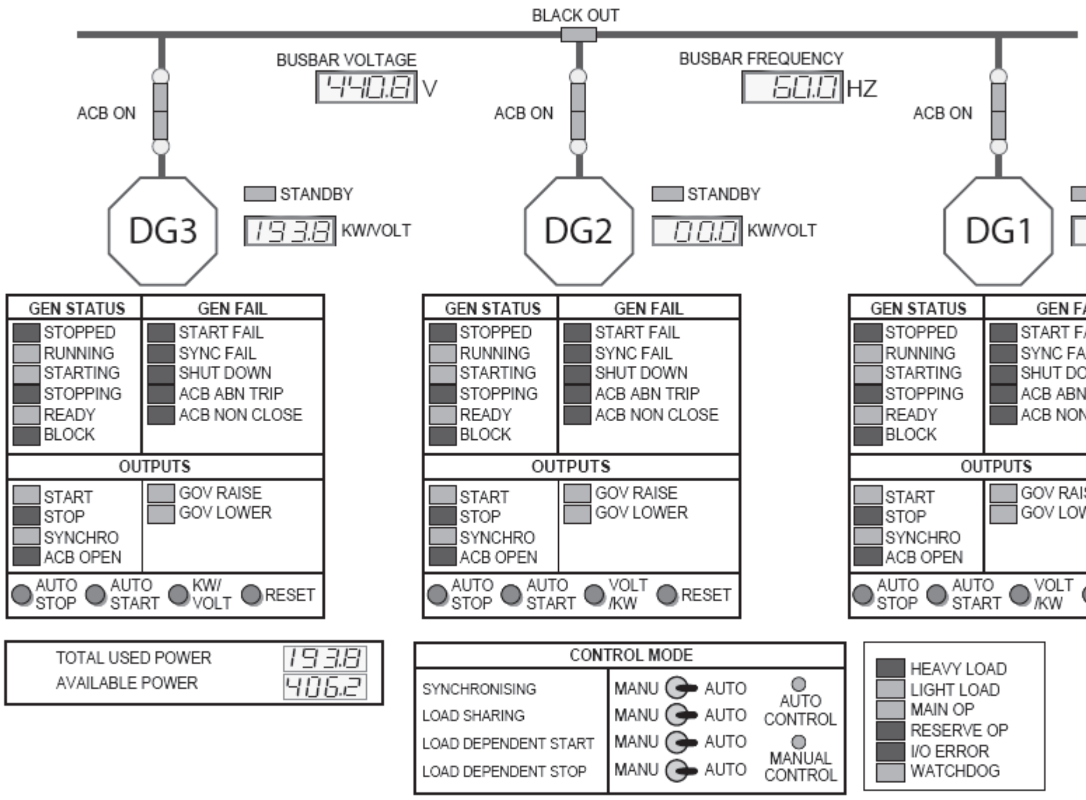

Fig. 2. Power Management System control monitoring panel 0

Neglecting the number of running diesel generators next diesel generator is activated once the 85% of nominal load is reached for each one in the absolute power margin option. For two generators running in the parallel mode with a load of 85% each one, the total power margin is 30%. In the system with a constant power margin with two diesel generators in parallel mode the power margin is only 15%. The next diesel generator is activated once the total load of running generators will reach 92.5%. If the constant power margin mode is used, the third generator is switched off with a relatively higher load that is 56.7% comparing to the 51.7% for the absolute power margin. Frequent and short time changeable load could cause intensive start and stop sequence of diesel generators. To avoid such situations the correct delay time and hysteresis offset is adjusted. The diesel generator stop signal is determined by the hysteresis value adjusted to 15% of the nominal electric power. That is why in table 4 with the constant power margin case the third diesel generator is switched off at the 30% of the total power margin and not 15% like it is in the start up sequence.

A good example of the correct electric power system's set ups in Power Management System (PMS) considering right load of the generator's reciprocating engine based on the specific fuel oil consumption SFOC (g/kWh), durability and tribology wear can be a 300 000 DWT tanker build in the Korean Shipyard. There are three diesel generators installed in the ship's engine room. Every diesel engine has 1395 kW nominal power that drives the generator with 1300 kW electric power. The power management system is designed in such a way that at 1170 kW load, which is 90% of nominal electric power, the next diesel generator is activated. If there is 1100 kW load or less for at least 5 minutes, the PMS automatically send a signal to stop one diesel generator.

6. Conclusions

The research of relationships between individual container ships' construction parameters and its products related to the electric power of diesel generators were carried out with Statistics application. The regression factors of the vessels' designed parameters have been determined based on the least squares method. The formula (5) for the total electric power was calculated with the test of 84 container carriers, where the electricity is produced only with diesel generators.

The number and the power demand of the reefer containers RC, the specific maximum continuous rating SMCR of the main propulsion engine as well as the number of diesel generators installed on board play the crucial role in the ship's total electrical power. Based on this knowledge, it is possible at the design stage, bring the ship's operational expenses down, lower the EEDI to the acceptable level and even lower, and finally reduce the GHG emissions considerably.

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